OPTIMAL SHORT-TERM GENERATION SCHEDULING OF ELECTRICAL POWER SYSTEM USING NOVEL HEURISTIC OPTIMIZATION TECHNIQUES

A SYNOPSIS

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1. INTRODUCTION

In the operation and planning of power systems, the optimal generation scheduling of available generating units is considered as an important task. The short-term hydro thermal scheduling (STHTS) optimization problem involves optimal generation scheduling of hydro and thermal units to meet load demand at minimum operating cost of thermal units, considering various constraints in the power system network. The duration for short-term hydrothermal scheduling covers various lengths from one day to one week with intermediate intervals. Hydro thermal scheduling is more complex than a thermal generation schedule. Since the operating cost of hydro units is nominal, the hydro reservoir water is used as much as possible and the scheduling problem is solved to minimize the operating cost of thermal plants.

The demand for fossil fuels used for thermal plant operation has increased due to the demand for electrical energy. But due to scarcity of fossil fuels, their prices have risen rapidly. Hence, considering the operating cost, climate change, and clean energy, the focus is on using alternative power sources including solar and wind power plants to meet the upcoming demand. Also, insignificant availability and waver nature of solar irradiation and wind speed can be compensated by adopting a power dispatch strategy and integrating energy storage system. Energy storage devices match energy production with consumption and build the energy balance in the power grid. Hence, it is very cheap, convenient, and safe to integrate conventional energy sources like thermal and hydro plants with renewable energy sources like wind plants and solar PV plants with battery energy storing system (BESS) in the same power network.

In this scheduling problem, various constraints such as reservoir storage limitations, reservoir inflow variations, water discharge rate limitations, hydraulic continuity constraints, power-generation limitations, power demand variations, solar irradiation variations, and variations in wind velocity are considered. In addition, other factors such as valve point loading in thermal plants, timing effect in the hydro subsystem, and transmission losses are taken into consideration. The above constraints and factors make this scheduling problem a non-convex and non-linear optimization problem.

Several deterministic methods have been used to solve the short-term hydrothermal scheduling problem. Some of the methods are listed below: Gradient Search, Lagrangian relaxation technique, and Dynamic programming. These methods solve the scheduling problem by considering the number of simple assumptions to obtain an efficient search operation.

Over the past few decades, meta-heuristic search techniques have been developed to obtain the optimal solution for STHTS problem and short-term hydro-thermal-solar-wind scheduling problem. Some of the methods are listed below: Simulated-annealing (SA), Genetic algorithm(GA), Evolutionary programming (EP), Differential evolution (DE), Tabu search (TS), Particle swarm optimization (PSO), Bacterial foraging algorithm (BFA) , Flower pollination algorithm (FPA), Grey wolf optimization (GWO), Ant lion optimization (ALO), Lightning attachment procedure optimizer, Sine cosine algorithm (SCA), Moth-flame optimization (MFO), and cuckoo search algorithm (CSA). These methods are effectively utilized to overcome many difficulties faced by classical methods due to its simple implementation process, applicability in seeking for the feasible solution, and capability to solve nonlinear optimization problems.

2. LITERATURE REVIEW

In previous years, several deterministic approaches have been reported for the solution of short term hydrothermal scheduling problem. Wood & Wollenberg [1] used the well documented method called gradient search method to find out the optimum hydro thermal generation schedule. Wang et al. [2] suggested an algorithm based upon augmented lagrangian relaxation approach developed in conjunction with decomposition and coordination method to resolve the problem of short term hydro thermal generation scheduling (STHTS) with environmental and transmission network constraints. Hoseynpour et al. [3] described an effective dynamic non-linear programming technique to achieve optimum results for a complex thermal and hydro scheduling problem in a short period of time.

Over the past few decades, popular stochastic search algorithms are reported for solving hydro thermal scheduling problem and hydro-thermal-solar-wind scheduling problem. Wong and Wong [4] demonstrated a coarse-grained parallel simulated annealing algorithm to attain an optimal solution for STHTS problem. Wu et al. [5] employed genetic algorithm based on diploid genotype model to achieve an optimal solution to the STHTS problem. Sinha et al. [6] employed gaussian and cauchy mutations based evolutionary programming technique, which were tested in complex hydro and thermal power plants having restricted operating zones. Basu [7] utilized an interactive fuzzy satisfying approach based on EP algorithm to solve multi objective short-term complex hydro thermal planning problem. Lakshminarasimman and Subramanian [8] developed a hybrid differential evolution (DE) technique in conjunction with equality constraint handling process to attain the best solution for the STHTS problem with various significant constraints. Sinha and Lai [9] demonstrated the performances of EP-

based algorithms and PSO technique in solving STHTS problem. Yu et al. [10] resolved the scheduling problem of thermal and hydroelectric system having numerous constraints by employing different PSO approaches. Mandal et al. [11] presented the PSO technique to attain the most favorable solution to a complex hydro thermal generating system scheduled to one day. Sanjeevikumar and Sudhakaran [12] proposed an Integrated GA-PSO-TS algorithm for solving hydro thermal scheduling problem with prohibited operating zones. Passino [13] introduced the BFA to solve various optimization problems. Farhat and Hawary [14] presented an improved BFA to resolve the classic thermal and hydro planning problem. Seyedali Mirjalili et al. [15] proposed a new meta- heuristic algorithm (GWO) to solve the optimization problem. Zhong-kai feng et al. [16] proposed an improved grey wolf optimizer technique, based on semi-adversarial learning, elite transformation, elastic-ball strategy, and heuristic restriction manipulation approach to attain optimal scheduling of two-tier hydro units.

In recent decades, popular heuristic search algorithms are reported for solving hydro-thermal-solar-wind scheduling problem. Basu [17] implemented a fast convergence real-coded genetic algorithm (FCRCGA) to achieve feasible generation planning in a thermal-hydro-solar-wind power structure with BESS. Dubey et al. [18] utilized an innovative nature-influenced optimization technique named ant lion optimization (ALO) to earn feasible fuel cost for a thermal-hydro-wind planning problem. Hazra and Roy [19] established a moth-flame optimization (MFO) method to cut down the operating cost and fuel emissions for a wind-thermal-hydro system. Nguyen et al. [20] presented a cuckoo search algorithm to receive the minimum fuel cost for an integrated thermal, hydro, and wind power structure. Mohamed et al. [21] proposed a lightning attachment procedure optimization (LAPO) technique to obtain the optimum fuel cost for a thermal-wind-hydro-photovoltaic (PV) power system. Dasgupta et al. [22] enforced a powerful sine cosine algorithm (SCA) to solve a short-term thermal- hydro-solar-wind planning problem to decrease fuel cost and fuel emissions.

Conventional methods are well documented and are widely used in different formulations to solve scheduling problems and provide effective results for smooth cost equations. These have certain drawbacks, such as difficulties in handling constraints, dimensional difficulties, more computation time, and trapping into local optimum are observed.

Evolutionary methods are easier to implement, derivative-free, robust, and often involve a limited number of parameter tunings. However, a few shortcomings such as large

computational time, slow convergence towards an optimal solution, and local optimization are noticed when applied in large dimensional and nonlinear problems

3. OBJECTIVE OF THE RESEARCH WORK

The main objectives of this research work are as follows:

- To develop a heuristic-based solution technique to solve short-term hydro thermal scheduling problem to minimize the operating cost of thermal power plants considering the constraints on maximum water resource utilization.
- To find the optimum schedule to meet the forecasted load demand and transmission line losses over the scheduling period while satisfying the various constraints imposed on the power system network.
- To propose hybrid techniques by combining PSO algorithm and improved bacterial foraging (IBF) algorithm to achieve optimal solution with lesser computation time for short-term hydro thermal scheduling problem.
- To develop a heuristic technique to solve short-term hydro-thermal-solar-wind power scheduling problem to reduce the operating cost of thermal power plants along with the cost of wind and solar plants.

4. RESEARCH PROBLEM

The given problem relates to the scheduling of hydro and thermal units, which consists of an objective function and several equality inequality constraints.

4.1 Objective function

The objective function (Eq. 4.1) is to reduce the operating cost of thermal power plants by meeting the load requirement and transmission line losses during the planning period with the consideration of various limitations imposed on the power network. The hydrothermal scheduling problem with short-time duration can be mathematically represented as follows.

$$\text{Minimize} \quad (F) = \sum_{j=1}^{N} n_j F_j(PT_j) \tag{4.1}$$

Where,

j=1, 2, 3….N schedule interval

$F_j(PT_j)$, represents the fuel cost of the thermal plant in $/h

n_j , denotes hours allotted in j^{th} interval subject to the following constraints

4.2 Equality constraints

The equality constraints such as power balance constraints, transmission losses, hydro power

and water discharge rate are defined in the following equations.

Power balance constraints:

$$P_{D_j} + P_{L_j} = P_{H_j} + P_{T_j} \tag{4.2}$$

Where the transmission line loss P_{L_j} is represented by

$$P_L = k(P_{H_j})^2 \tag{4.3}$$

The hydro power depends upon the water discharge rate only and given as

$$q_j = g(P_{H_j}) \tag{4.4}$$

Total water discharge rate is defined by

$$\sum_{j=1}^{jmax} n_j q_j = q_{TOT} \; : \tag{4.5}$$

$$q_{TOT} = (V_s + r_{nj}) - V_{end} \tag{4.6}$$

Reservoir volume (Hydraulic continuity equation)

The STHS optimization problem includes the limitations of hydro plant discharge and reservoir storage volumes. The reservoir volume is given by the following equations

$$V_{j+1} = V_j + (n_j - q_j - s_j) \tag{4.7}$$

The scheduling problem also include the initial and final reservoir storage volumes which is formulated as follows: The Initial and final reservoir storages are given as

$$V_j(0) = V_s \quad \text{and} \quad V_j(end) = V_{end} \tag{4.8}$$

4.3 Inequality constraints:

The water discharge rate, thermal generation limits, hydrogenation limits and reservoir storage limits are considered as an inequality constraints which are represented in the following equations

Water discharge rate limits

$$q_{j_{min}} < q_j < q_{j_{max}} \tag{4.9}$$

Thermal generation limits

$$P_{T_{j_{min}}} < P_{T_j} < P_{T_{j_{max}}} \tag{4.10}$$

Constraints on hydro generation

$$P_{H_{j_{min}}} < P_{H_j} < P_{H_{j_{max}}} \tag{4.11}$$

Reservoir storage limits

$$V_{min} < V_j < V_{max} \tag{4.12}$$

The hydrothermal scheduling problem is considered as nonlinear, non-convex multi – dimensional optimization problem in addition to linear, non-linear and dynamic network flow constraints.

4.4 Prohibited operating zones (POZs)

There are many physical components such as shaft, gear etc. involve in thermal and hydro generator. The physical limitations of the components in the power plant may enforce a prohibited operating zone. The rotating and non-rotating parts of the generator may vibrate at certain range of frequencies. If the vibration frequency matches to the natural frequency of the components then resonance occurs which in-turn lead to wild fluctuation with components damage. The power outputs during the resonance phenomenon are known as POZs. In other words the hydrothermal units should not be operated in the specific POZs. The unit should be operated either above or below these POZs.

The prohibited zones for operating the power plant unit j are framed as below.

$$P_{j,z}^{L} \leq P_j \leq P_{j,z}^{U} \qquad z = 1,2,3 \dots \dots \dots n_j \tag{4.13}$$

Where, j = generating unit index

P_j = unit generation

n_j = total number of avoidable operating zones for unit j

n_j = prohibited operating zones' index for unit j

$\mathrm{P}_{\mathrm{j},z}^{\mathrm{L,U}}$ = lower and upper limits of the z^{th} avoidable zones for unit j

5. DESCRIPTION OF THE RESEARCH WORK CARRIED OUT

(a) Short-term hydro thermal scheduling using Flower pollination algorithm

In this work, flower pollination algorithm (FPA) is used to solve the hydrothermal scheduling problem considering short term duration. This is a large-scale nonlinear dynamic optimization problem with various operating limits. FPA is a new stochastic technique, which follows the evolutionary characteristics of flower pollination. The purpose of flower pollination is to reproduce the flowering plants. This algorithm follows the levy flight mechanism for generating the population for the subsequent generation. The proposed work is illustrated and tested with standard test example, which consists of a hydro plant and an equivalent thermal plant and the results are compared with other optimization methods. The test results show that this optimization algorithm gives better solution with shorter

processing time. The performance of the proposed algorithm clearly depicts that the algorithm has a greater balance between diversification and intensification, during the search for best optimum results.

(b) Short-term hydro thermal scheduling using Flower pollination algorithm with prohibited operating zones

In this work, an effective stochastic method called Flower pollination algorithm (FPA) is implemented to arrive at the perfect solution. This algorithm has the evolutionary characteristics of pollinating process of flowers such that fittest members will survive and the subsequent generation of the healthier flowering plants. FPA executes the levy flight transport to generate members in the successive generation. To evaluate the efficacy of this algorithm, it is put forth to a standard test case by considering hydro and thermal power plant with a time slot of twelve hours interval on three days and simulated using the MATLAB software. Prohibited operating zones are included as additional constraints. The simulation results reveal that this meta-heuristic algorithm yields best outcome in minimum executing time than the other heuristic methods

(c) Combined PSO and IBF algorithm for short-term hydro thermal scheduling

In this research work, a combined particle swarm optimization (PSO) and improved bacterial foraging algorithm (IBFA) is proposed for the above short term hydro thermal scheduling (STHTS problem with prohibited operating zones (POZs). The simulation result shows that the combined PSO-IBF algorithm yields minimum cost value and optimal convergence rate than the existing algorithms.

(d) Short term complex hydro thermal scheduling using integrated PSO-IBF algorithm

In this wok, an integrated evolutionary technique such as particle swarm optimization (PSO) algorithm and improved bacterial foraging algorithm (IBFA) have been developed to provide an optimum solution to the scheduling problem with complex thermal and hydro generating stations. PSO algorithm is framed based on the intelligent behavior of the fish school and a flock of birds and the optimal solution in the multidimensional search region is achieved by assigning a random velocity to each potential solution (called the particle). BFA is designed by following the prey-seeking (chemotactic) nature of E. coli bacteria. This technique is followed in an improved manner to get the convergence rate in dynamic for a hyperspace problem by implementing a chemotactic step in a linearly decreased way instead of the static one. The effectiveness of this integrated algorithm is evaluated by using it in a complex thermal and hydro generating system. In this testing system, multiple numbers of cascaded reservoirs in hydro plants have a time coupling effect and thermal power units have

a valve point loading effect. The simulation results indicate its merits by comparing it with other meta-heuristic techniques related to the fuel cost required to generate the thermal power.

(e) Optimum generation scheduling of thermal and hydro power system with renewable power sources using Enhanced grey wolf optimization algorithm

In this work, an algorithm of enhanced grey wolf optimization (EGWO) is implemented to resolve the scheduling problem of a power system, which is having thermal, hydro, wind, and solar power plants with a battery energy storing system (BESS). The planning period covers 24 equal intervals of a day. In this scheduling problem, the impact on valve point loading of thermal generating plants, the time coupling effect in cascaded reservoirs of hydro units, and various constraints imposed on the power network are taken into consideration. The grey wolf optimization (GWO) technique is used, which is framed on the group attitude of grey wolves such as governance ranking and hunting activity. In this proposed algorithm, the quasi-oppositional learning approach is exploited to obtain the optimal solution quickly. Also, the elite mutation operator is applied to maximize the diversity of the swarm. In addition, by implementing the elastic-ball strategy, infeasible solutions are modified into feasible one. The potential of the EGWO technique is ascertained by employing it in two experimental settings. From the simulation outcome, it is inferred that the implemented technique bestows less operating cost as compared to other evolutionary techniques.

6. SIMULATION RESULT

6.1 Short-term hydro thermal scheduling using Flower pollination algorithm

The proposed FPA is evaluated on a standard test system [1] which consists of a hydro plant and an equivalent thermal plant and the fuel cost function of the thermal plant is given in dollars per hour as follows:

$$F(P_T) = 575 + 9.20\,P_T + 0.00184\,P_T^2 \quad (6.1)$$

$$1500 \geq P_T \geq 150$$

The hydro power generation relationship to water discharge is denoted as,

$$q = 330 + 4.97\,P_H; \qquad 1000 \geq P_H \geq 0 \quad (6.2)$$

$$q = 5300 + 12\,(P_H - 1000) + 0.05\,(P_H - 1000)^2 \quad (6.3)$$

$$1100 \geq P_H \geq 1000 \qquad q=0 \qquad \text{if } P_H = 0 \quad (6.4)$$

Table 1 and Table 2 gives hydro plant data and load curve data with three days' twelve hour schedule respectively.

Table 1 Hydro plant data

V_{min} acre-ft	V_{max} acre-ft	V_{start} acre-ft	V_{end} acre-ft	q_{min} acre-ft/hr	q_{max} acre-ft/hr	r acre-ft/hr
60000	120000	100000	60000	330	7000	2000

Table 2 Load demand data

Interval No.	Day	Period	Demand(MW)
1	1st day	0-12:00hr	1200
2	1st day	12:00-24:00hr	1500
3	2nd day	0-12:00hr	1100
4	2nd day	12:00-24:00hr	1800
5	3rd day	0-12:00hr	950
6	3rd day	12:00-24:00hr	1300

Transmission loss is very less and spillage rate is assumed to be zero. The results are obtained from MATLAB and shown in Table 3. The fitness value characteristics of the proposed method are shown in Figure 1.

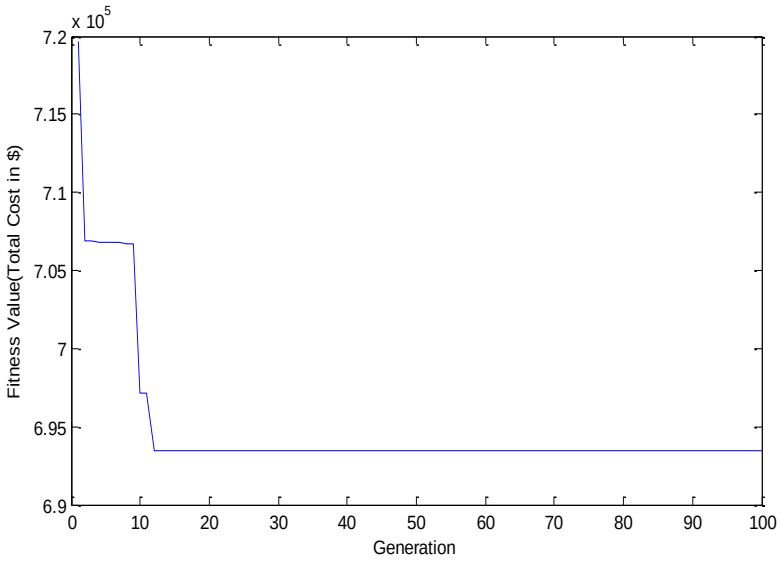

Figure 1 Convergence Characteristics of the FPA Method

Table 3 Result of the Proposed Method

Discharge rate as control parameters					
Interval	**PT (MW)**	**PH (MW)**	**Volume (acre-ft)**	**Discharge rate (acre-ft/hr)**	**Cost($)**
1	806.299	393.700	96559.705	2286.691	693427. 160
2	805.796	694.203	75197.387	3780.193	
3	1100	0	99197.387	0	
4	806.754	993.245	60000.211	5266.431	
5	950	0	84000.211	0	
6	561.566	738.433	60000.013	4000.016	

By comparing the outcome of the proposed algorithm with earlier works, reduction in cost is achieved in this method.

Table 4 Comparison of Results

S.No	**Author**	**Method**	**Cost ($)**
1	Wood A.J	GS [1]	709877.38
2	Wong.K.P.et.al.	SA [4]	709870.46
3	Sinha.et.al.	IFEP [6]	709862.05
4	Nidul Sinha.et.al	PSO [9]	709862.048
	Sanjeevkumar.et.al	GA-PSO-TS [12]	709862.0
5	Farhat.et.al	BFA [14]	709837.926
6	Proposed	FPA	693427.16

Table 4 shows various optimization techniques previously carried out. It is obvious that this proposed FPA algorithm is highly effective and gives near global solution compared to other deterministic and heuristic algorithms. Apart from this algorithm gives global optimum with fast convergence rate. This proposed algorithm has a greater balance between diversification and intensification, during the search process.

6.2 Short term complex hydro thermal scheduling using integrated PSO-IBF algorithm

The proposed integrated PSO-IBF algorithm has been implemented in to a standard testing system adopted in previous works [11] and resolved using the MATLAB software. The test system comprises of three thermal power stations with a valve point loading effect

and four multi-chain cascaded hydro plants with a time coupling effect. The scheduling period for hydrothermal plants has been assigned as 24-time slots with a one-hour interval for each time slot. Assuming spillage rate and transmission line loss is zero.. The power demand data, power production parameters of hydro plant, hydro reservoir inflows, hydro plant data with power generation limits and cost curve parameters with generation limits of thermal plants are shown in Tables 5- 9 respectively. The hydro reservoirs water time delay data matrix is shown in Table 10.

Table 5 Load demand data

Time slot	Demand (MW)	Time slot	Demand (MW)	Time slot	Demand (MW)
1	750	9	1090	17	1050
2	780	10	1080	18	1120
3	700	11	1100	19	1070
4	650	12	1150	20	1050
5	670	13	1110	21	910
6	800	14	1030	22	860
7	950	15	1010	23	850
8	1010	16	1060	24	800

Table 6 Hydroelectric power production coefficients

Plant	C_1	C_2	C_3	C_4	C_5	C_6
1	-0.0042	-0.42	0.030	0.090	10.0	-50
2	-0.0040	-0.030	0.015	1.14	9.5	-70
3	-0.0016	-0.30	0.014	0.55	5.5	-40
4	-0.0030	-0.31	0.027	1.44	14.0	-90

Table 7 Hydro plant reservoir inflows ($\times 10^4$ m^3)

Time slot	Reservoir inflows				Time slot	Reservoir inflows				Time slot	Reservoir inflows			
	1	2	3	4		1	2	3	4		1	2	3	4
1	10	8	8.1	2.8	9	10	8	1	0	17	9	7	2	0
2	9	8	8.2	2.4	10	11	9	1	0	18	8	6	2	0
3	8	9	4	1.6	11	12	9	1	0	19	7	7	1	0
4	7	9	2	0	12	10	8	2	0	20	6	8	1	0
5	6	8	3	0	13	11	8	4	0	21	7	9	2	0

6	7	7	4	0	14	12	9	3	0	22	8	9	2	0
7	8	6	3	0	15	11	9	3	0	23	9	8	1	0
8	9	7	2	0	16	10	8	2	0	24	10	8	0	0

Table 8 Hydro plant data ($\times 10^4\ m^3$) and generation limit (MW)

Plant	V^{min}	V^{max}	V_{ini}	V_{end}	Q^{min}	Q^{max}	P_h^{min}	P_h^{max}
1	80	150	100	120	5	15	0	500
2	60	120	80	70	6	15	0	500
3	100	240	170	170	10	30	0	500
4	70	160	120	140	6	20	0	500

Table 9 Cost curve factors and thermal power production limits

Unit	a_s ($ / h)	b_s ($ / (MW h)	c_s ($ / $(MW)^2$h)	d_s ($ / h)	e_s ($1MW^{-1}$)	P_s^{min} (MW)	P_s^{max} (MW)
1	100	2.45	0.0012	160	0.038	20	175
2	120	2.32	0.0010	180	0.037	40	300
3	150	2.10	0.0015	200	0.035	50	500

Table 10 Hydro sub system specifications

Plant	1	2	3	4
R_u	0	0	2	1
t_d	2	3	4	0

R_U : Sum of overhead units

t_d : Delay time to next down head unit

The optimal thermal and hydro and power generation schedule of the PSO algorithm is displayed in Table 11.

Table 11 Hydro thermal generation schedule using PSO

Hour	P_{h1} (MW)	P_{h2} (MW)	P_{h3} (MW)	P_{h4} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	Cost($)
1	48.80	43.83	27.61	32.80	43.83	201.32	351.81	45150.36
2	81.65	51.69	38.15	63.65	51.70	109.05	384.10	
3	232.63	56.07	33.29	222.63	56.07	43.90	65.41	
4	39.59	45.45	41.78	19.59	45.46	292.95	55.18	
5	115.58	71.04	30.23	104.58	71.04	213.65	63.90	
6	53.17	46.98	37.48	40.17	46.98	62.78	500.44	
7	23.24	26.05	55.35	6.25	26.05	294.61	258.45	
8	43.86	49.95	76.58	27.86	49.95	42.43	499.37	
9	179.34	46.68	28.28	169.35	46.68	251.47	368.19	
10	59.12	57.45	42.74	46.12	57.45	41.59	497.54	
11	78.40	72.81	37.44	67.40	72.81	299.70	51.44	
12	20.30	31.72	42.86	5.30	31.72	51.93	496.16	
13	179.38	54.76	36.58	165.39	54.76	185.64	433.50	
14	181.03	54.93	87.25	163.03	54.93	62.54	426.30	
15	179.10	42.08	28.01	169.10	42.08	145.48	404.16	
16	58.25	51.62	29.96	47.25	51.62	298.56	312.72	
17	205.87	41.87	48.79	188.88	41.87	189.86	332.85	
18	32.84	38.99	25.71	22.84	38.99	41.85	498.78	
19	281.27	54.41	33.26	271.27	54.42	228.26	147.11	
20	109.96	52.85	57.50	91.96	52.85	58.66	496.22	
21	280.98	72.56	35.90	264.98	72.56	107.02	75.99	
22	40.32	62.13	38.52	24.32	62.13	230.14	402.45	
23	184.63	19.07	27.52	172.63	21.07	289.59	87.50	
24	55.51	54.01	82.73	40.51	54.02	40.45	482.76	

The cost ($) obtained by using the PSO algorithm is 45150.36. The effect of cost characteristics derived from the PSO technique is shown in Figure 2 and it is identified that with fewer iterations, this algorithm converges to the optimum value. Thus the PSO approach is considered optimal in terms of feasibleness and processing time.

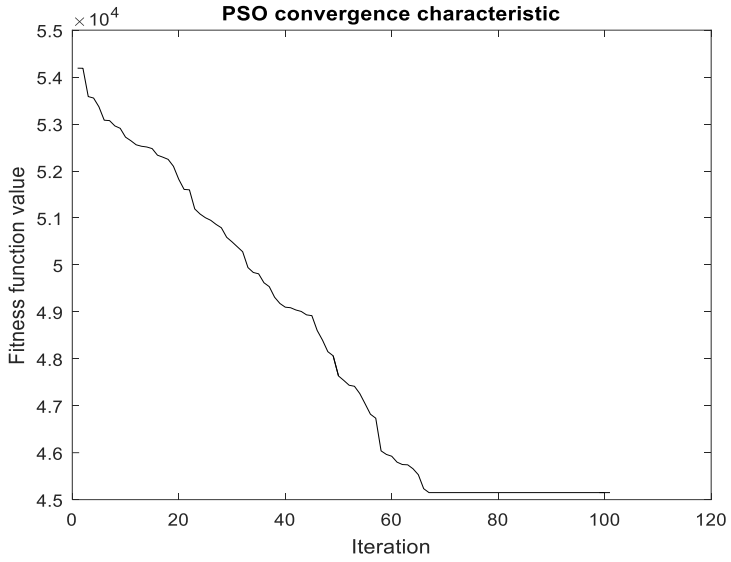

Figure 2 PSO convergence characteristics

Table 12 display the power station production schedule and water release rate of the IBF algorithm.

Table 12 Hydro thermal generation schedule using IBFA

Hour	P_{h1} (MW)	P_{h2} (MW)	P_{h3} (MW)	P_{h4} (MW)	P_{s1} (MW)	P_{s2} (MW)	P_{s3} (MW)	Cost($)
1	53.66	81.37	176.77	146.83	43.97	94.29	153.11	43095.46
2	144.22	40.89	104.24	206.79	174.59	42.64	59.63	
3	140.38	29.00	140.52	119.10	173.28	55.87	53.85	
4	72.08	89.08	83.97	94.72	53.84	100.26	156.05	
5	136.99	70.33	52.29	75.18	173.26	46.03	82.92	
6	58.03	156.32	132.67	127.20	80.06	150.53	95.19	
7	195.40	70.97	74.92	142.03	123.97	137.22	205.49	
8	107.69	143.16	155.75	226.23	174.09	80.72	80.36	
9	120.48	178.05	183.65	136.63	110.35	145.05	215.78	
10	124.29	136.21	231.32	203.09	122.97	225.60	56.51	
11	114.85	89.55	208.09	173.97	174.94	214.07	84.53	
12	232.45	56.08	133.42	282.51	125.44	238.17	81.93	

13	165.93	296.95	117.83	120.91	85.76	110.72	211.90	
14	131.47	208.73	111.32	191.85	123.92	142.40	120.30	
15	65.37	119.32	170.95	153.85	152.84	191.46	156.20	
16	118.50	214.83	149.82	30.09	173.76	69.35	243.66	
17	257.30	127.26	170.53	165.80	79.55	148.53	101.02	
18	202.15	118.30	72.27	142.61	121.35	221.48	241.84	
19	38.46	272.93	152.24	247.78	79.30	252.42	56.87	
20	186.49	223.38	70.06	175.37	90.08	77.01	227.59	
21	128.40	140.24	112.83	88.05	114.31	160.32	165.84	
22	94.55	171.96	180.64	97.56	85.01	46.21	184.08	
23	127.05	108.97	139.18	138.71	143.85	113.06	79.18	
24	91.61	130.80	93.76	83.83	160.67	156.10	83.24	

The final fuel cost value received from the IBF algorithm is 43095.46 $. Figure 3 portrays the cost characteristics obtained from the IBF algorithm. It has been revealed that this algorithm offers the lowest cost value at a faster convergence rate compared to other algorithms.

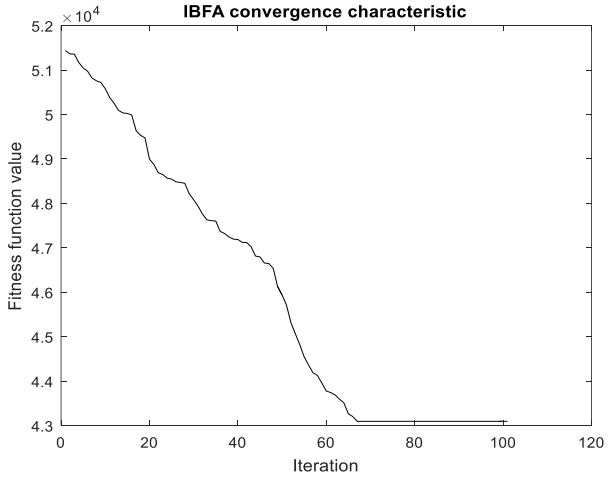

Figure 3 IBFA convergence characteristics

Table 13 provides the comparative results of the proposed integrated approach with other stochastic algorithms.

Table 13 Comparative results of different optimization algorithms

S.No	Authors	Technique	Cost ($)
1	K.K.Mandal. et.al	EP [11]	47,306
2	K.K.Mandal. et.al	SA [11]	45,466
3	K.K.Mandal. et.al	PSO [11]	44,740
4	Balachander. et.al	Proposed PSO-IBFA	43, 095

It is known from the comparative results that the propounded PSO-IBF algorithm bestows a globally optimal solution with minimal calculation time than the other optimization techniques. In this proposed technique, a dynamic decreasing function is applied to update the solution path, thus greatly improving the convergence properties. Hence it is proved that the PSO-IBF algorithm possesses the potential to obtain the best possible solution with nominal time for the complex STHTS problems.

6.3 Optimum generation scheduling of thermal and hydro power system with renewable power sources using Enhanced grey wolf optimization algorithm

In this work, an enhanced grey wolf optimization (EGWO) algorithm has been implemented for solving the short-term thermal, hydro, solar, wind, and a battery energy storing system (BESS) scheduling problem. This test system comprised of thermal units with valve point loading impact, four hydro plants with timing effect, one solar PV plant, one wind power plant and one BESS. The duration of the planning is selected as one day with 24 intermediate intervals. Transmission losses in line are taken into account while spillage rate is assumed to be zero.. The hydro subsystem data, hydro plant power generation parameters, reservoir inflows, hydro unit data and its output power limits, cost function coefficients and output power limits of thermal units are taken form section 6.2. Various parameters related to wind and solar PV plants are given below:

6.3.1 Data for wind and solar PV plant

P_{wr} = 150 MW, v_{in} = 4m/sec, v_o =25 m/s v_r = 115 m/s, K_w = 3.25

P_{PV_r} = 150 MW, K_s = 3.5, G_{std} = 1000, R_c = 150 W/m^2, P_b^{max} = 100 MW

The parameters of GWO and EGWO algorithm are chosen as follows: number of population is 50; maximum number of iterations is 300

The optimum thermal, hydro, solar, and wind power production schedule of the EGWO algorithm for test system 1 are presented in Table 14.

Table 14 Thermal, hydro, solar and wind power production schedule using EGWO for test system1

Hour	Ps1 (MW)	Ps2 (MW)	Ps3 (MW)	Ph1 (MW)	Ph2 (MW)	Ph3 (MW)	Ph4 (MW)	Pw (MW)	Ppv (MW)	Pb (MW)	Ploss (MW)	Load (MW)
1	54.8418	81.7491	105.6565	104.3284	102.9839	103.5673	98.7611	0	0	89.5385	8.5745	750
2	48.7799	87.5598	126.3397	112.6909	116.3948	117.0636	104.5787	0	0	58.8594	7.7682	780
3	35.9727	53.5673	71.1619	109.3324	122.3121	121.3579	102.568	0	0	73.671	10.1109	700
4	31.3419	63.6839	95.0258	99.1497	101.6672	103.0016	100.8091	0	0	43.5166	11.8689	650
5	41.5437	56.3298	71.1159	102.5738	104.0541	104.2216	103.2351	0	0	75.8451	11.1283	670
6	42.4239	84.8477	127.2716	117.5712	126.0266	124.8495	119.3352	0	0	50.339	7.3377	800
7	60.2384	129.1309	198.0233	153.8486	158.2863	153.2774	150.3365	0	12.321	-71.0624	5.6561	950
8	53.1645	134.6742	216.1839	160.3252	163.7496	160.9167	159.181	0	46.65	-90.3572	5.5179	1010
9	57.3698	140.5356	241.0384	170.1018	168.5157	167.6643	167.3966	0	56.25	-85.5341	6.7516	1090
10	61.3107	148.2477	237.4366	158.5133	160.919	158.0527	152.4093	0	75.45	-78.7532	6.4703	1080
11	62.4453	128.7463	243.7463	160.4349	162.3338	162.2554	160.2465	0	92.55	-79.7806	7.0679	1100
12	72.388	158.6714	249.8212	188.2526	192.2459	188.3573	188.0659	0	2.9	-99.6644	8.987	1150

13	50.55	133.4099	216.2699	168.2739	172.6624	176.7652	175.5708	0	105.45	-96.2936	7.4193	1110
14	49.3678	126.1743	215.6548	129.8571	143.3559	133.2514	142.2481	60	110.4	-85.8399	5.6231	1030
15	59.6981	120.6618	191.3255	135.2413	142.636	143.2252	128.2867	80.4545	87.9	-84.8535	5.5179	1010
16	58.5899	126.6635	203.9371	147.6076	150.9984	154.082	150.7334	83.1818	63.75	-85.5395	6.013	1060
17	52.1585	127.8798	203.601	155.3529	155.0401	158.1188	150.2495	77.7273	43.65	-79.5874	5.837	1050
18	54.7364	124.299	249.299	172.3751	179.675	175.2493	174.409	70.9091	7.396	-96.1172	7.8012	1120
19	57.9774	137.5123	217.0471	161.6332	162.1152	160.1856	161.2985	76.3636	0	-70.3427	6.2241	1070
20	53.0436	131.8429	210.6421	166.1859	164.6604	166.7272	165.2107	81.8182	0	-95.8933	5.837	1050
21	51.7484	107.4866	163.2249	143.1614	141.6291	146.6928	145.2484	81.6182	0	-76.6406	5.9009	910
22	48.8799	97.7597	146.6396	136.1651	137.6266	139.5873	136.2867	75	0	-64.2558	6.3901	860
23	44.6622	96.2269	148.7915	143.6414	146.2045	144.3229	133.3239	80.4545	0	-94.1045	6.4991	850
24	29.1911	53.6511	78.1111	111.2794	110.8697	103.1851	106.2169	117.273	0	82.9294	7.3377	800

The cost convergence properties attained from the GWO and EGWO algorithms are portrayed in Figure 4. It is obvious from Figure 4 that EGWO has a quick convergence rate to

reach an optimal solution. The fuel cost decreases promptly in the starting iterations and then step by step moves to the optimal solution. The fuel cost of test system 1 using GWO and EGWO is 38,910 and 38,520 respectively.

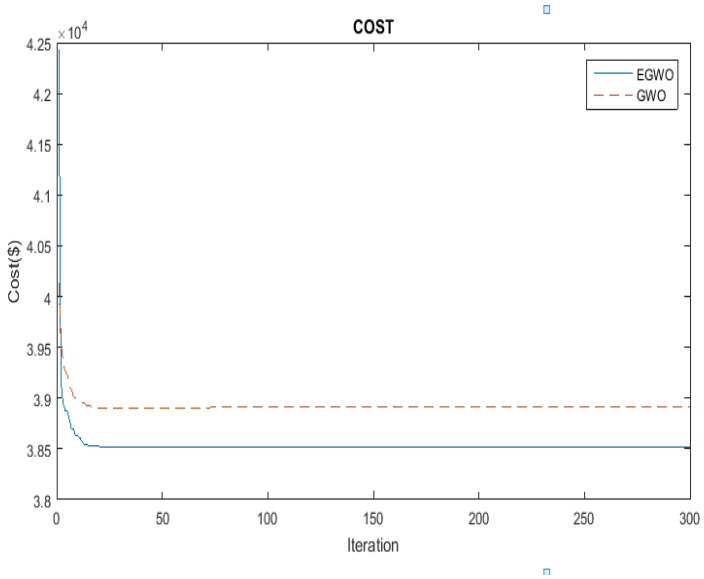

Figure 4 GWO and EGWO convergence characteristics for test system 1.

Table 15 shows the comparison of fuel cost of the suggested technique with various heuristic techniques for test system 1.

Table 15. Comparative results of the suggested technique with different heuristic technique for test system 1.

Sl.No	Method / Test 1	Cost ($)	Execution Time (s)
1	RCGA [17]	45327.96	35.09
2	FCRCGA [17]	44981.49	27.52
3	GWO	38910	21.56
4	Enhanced - GWO	38520	20.75

Table 15 shows the comparison of fuel cost of the proposed scheme with various heuristic techniques for test system 1. It clearly reveals that the proposed EGWO method is computationally more proficient and can reach the global optima faster than the GWO method and other random search algorithms. Due to the three efficient strategies combined with proposed technique, a feasible solution is quickly obtained in propitious regions of the solution area.

7. ORGANIZATION OF THE THESIS

The framework of the thesis is given below:

Chapter 1 briefly explains about the short-term hydro-thermal scheduling and the need of renewable energy sources for hydro-thermal scheduling, various constraints, classification of conventional methods and heuristic search algorithms to solve the hydro thermal scheduling problem.

Chapter 2 describes a comprehensive study of recent literature available on STHTS problem and its solutions. The STHTS problem is solved by application of different techniques, either by classical mathematical programming methods or heuristic search techniques. This literature survey has shown optimal solutions obtained by application of different heuristic and meta-heuristic techniques for various test systems.

Chapter 3 describes the mathematical modelling of power plants for optimal scheduling.

Chapter4 focuses mainly on the implementation flower pollination algorithm (FPA) to solve the hydrothermal scheduling problem with short duration. The new algorithm is compared for its performance with GA and PSO algorithms and results show the FPA is more efficient than both GA and PSO and the convergence rate is almost exponential.

Chapter 5 describes the hybrid PSO-IBF algorithm to solve the simple STHTS problem which includes the POZs as additional constraints.

Chapter 6 describes an integrated evolutionary technique such as particle swarm optimization (PSO) algorithm and improved bacterial foraging algorithm (IBFA) have been developed to provide an optimum solution to the scheduling problem with complex thermal and hydro generating stations.

Chapter 7 explains an algorithm of enhanced grey wolf optimization (EGWO) to resolve the scheduling problem of a power system, which is having thermal, hydro, wind, and solar power plants with a battery energy storing system (BESS).

Chapter 8 summarizes the research findings and significant research contributions. It also presents some area for future research work and concludes the thesis.

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22. K Dasgupta , PK Roy, V Mukherjee, “Solution of short term integrated hydro thermal-solar wind scheduling using sine cosine algorithm,” *Energy Strategy Reviews*, **40** (2022), 100824.

LIST OF PUBLICATIONS

1. T.Balachander, P.Aruna Jeyanthy, D.Devaraj, *"Short Term Hydro Thermal Scheduling using Flower Pollination Algorithm,"* Proceedings of the 2017 IEEE International Conference on Intelligent Techniques in Control , Optimization & Signal Processing, INCOS -2017, (2017), 1-5.
2. T.Balachander, P.Aruna Jeyanthy, D.Devaraj, *"Application of Flower Pollination Algorithm for solving Short Term Hydro Thermal Scheduling Problem with Prohibited Operating Zones,"* 2019 IEEE International Conference on Intelligent Techniques in Control , Optimization & Signal Processing, INCOS-2019, (2019), 1-5.
3. T.Balachander, P.Aruna Jeyanthy, D.Devaraj, "Combined PSO and IBF Algorithm for Short Term Hydro Thermal Scheduling,'' *International Journal of Recent Technology and Engineering (IJRTE),* **8** (4S2) (2019), 418-424.
4. T.Balachander, P.Aruna Jeyanthy, D.Devaraj, " Short term complex hydro thermal scheduling using integrated PSO-IBF algorithm,'' *Indonesian Journal of Electrical Engineering and Informatics (IJEEI),***10** (2) (2022), 232-245.
5. T.Balachander, P.Aruna Jeyanthy, D.Devaraj, "Optimum Generation Scheduling of Thermal and Hydro Power System with Renewable Power Sources using Enhanced Grey Wolf Optimization Algorithm," *Electric Power Components and Systems*, (2023), 1-18.